Life Cycle Assessment of Thermal Plasma Methane Pyrolysis

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Abstract:
With the growing role of thermal plasma in electrifying the industry, and in particular, with methane pyrolysis via thermal plasma gaining momentum in the energy transition for the coproduction of hydrogen and carbon-black, a life cycle assessment is conducted to evaluate the environmental performance of turquoise hydrogen produced using thermal plasma. The carbon intensity of hydrogen is calculated for a base case using fossil natural gas with 1.5% of leak rate and wind power. An alternative case is also evaluated where fossil natural gas is blended or completely replaced by renewable natural gas. Results show that the carbon intensity of turquoise hydrogen via thermal plasma is around 91% lower than that of hydrogen produced by steam methane reforming, and becomes carbon neutral when blended with 8-18% renewable natural gas.

Keywords: LCA, Thermal Plasma, Hydrogen, Methane Pyrolysis

1. Introduction

In light of meeting the Paris Accord target of keeping global temperature rise to less than 1.5 degrees Celsius, and in light of the recently adopted green policies and strategies such as the Inflation Reduction Act in the USA and REPowerEU and FF50 in the EU, electrifying the industry sector is becoming critical to reduce the emissions associated with it.

In particular when it comes to electrifying the industry, thermal plasmas are among the only solutions available able to convert electrical energy to thermal energy, providing a tuneable enthalpy for endothermic processes. One direct application for thermal plasmas that is rapidly gaining interest is the pyrolysis of methane for the coproduction of turquoise hydrogen and carbon black. Other than being a potential alternative for the currently high emitting carbon black production through incomplete oil combustion, methane pyrolysis via thermal plasma is also interesting from a hydrogen perspective, as compared to green hydrogen, it is significantly less energy intensive, requiring 7.5 times less energy as can be seen from equations (1) and (2) (38 kJ/mol H_2 vs 285 kJ/mol H_2)

$$CH_4 \rightarrow C + 2H_2 \quad (1)$$

$$H_2O \rightarrow H_2 + \frac{1}{2}O_2 \quad (2)$$

The reason for this is the energy contained in the methane molecular bonds. A representation of the process is shown in Figure 1. Using electrical input, the plasma arc is formed, reaching temperatures of >10,000 degrees C, decomposing methane into carbon-black and hydrogen at a very high conversion rate [1].

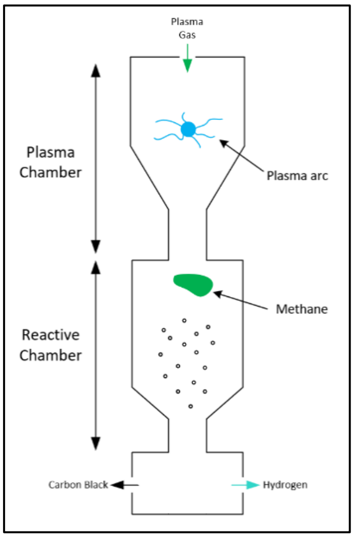

Fig. 1. Methane Pyrolysis via Thermal Plasma

This process has recently gained momentum, being cited in several international reports such as the IEA's global hydrogen review [2]. In practice, after several years of continuous R&D development, Monolith Materials, Inc, developed the first industrial plant, Olive Creek 1, in Nebraska, capable of producing 4.6 kilotons of hydrogen annually. Moreover, Monolith received conditional approval of $1.04 billion from the US department of energy for its future Olive Creek 2 facility with a production capacity around 12 times that of its first plant.

Thus, it is clear that methane pyrolysis via thermal plasma may potentially play an impacting role in the energy transition. It is therefore crucial to assess the environmental viability of this process over its life cycle.

Only one study included a life cycle assessment of methane pyrolysis via thermal plasma [3], concluding that the main parameters affecting the environmental performance of this technology are natural gas sourcing and the source of the electricity used. However, the study assumes that the co-produced carbon black is non-useable and therefore allocates all the impacts on hydrogen.

Therefore, this proceeding reports the first thorough life cycle assessment on methane pyrolysis via thermal plasma for the coproduction of hydrogen and valuable carbon-black. Part of the results have been published in a journal article in the International Journal of Hydrogen Energy [4].

2. Methodology

2.1. Process Flow Diagram:

Methane pyrolysis via thermal plasma is presented in Figure 2. Natural gas and other hydrocarbons are used as process input, pyrolyzed by the electric plasma arc. The resultant stream is then split into a hydrogen purification unit, and a carbon black back-end unit, for the coproduction of hydrogen and carbon black.

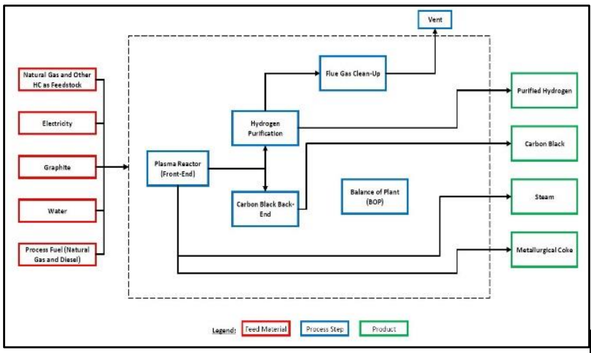

Fig. 2. Process Flow Diagram of Olive Creek 1 [4]

2.2. Data:

Compared to the majority of life cycle assessment studies where data is taken from laboratory-scale experiments, this study uses industrial data taken from Monolith's Olive Creek facility, as it is the only available commercial plant for this process.

Data used is for the annual production of 180,000 tons of carbon-black and 42,300 tons of hydrogen, using 259,000 kilotons of natural gas.

In total, 1250.2 GWh of electricity is used, with 1171.6 mmbtu of natural gas as process fuel and 364.6 Mgal of water.

2.3. Hypotheses:

Hypotheses are based on GREET2020 average values for the US and based on the California LCFS model. The main hypotheses can be summarized as follows:

- Regarding the natural gas supply chain, methane content is taken as 92% of the gas, with average emissions of 1.5% leaks
- GWP-100 metric is used
- Electricity is taken as wind power electricity with 10 gCO2e/kWh

2.4. Allocation Method and Scope Definition:

Considering that there are two coproducts for the process, allocating total emissions among the products should be conducted based on a standardized methodology. The chosen allocation method is the mass allocation, as it gives more stable results compared to the economic allocation with the current fluctuations of natural gas prices.

As for the scope definition, three scopes are defined according to the ISO 14040 and the GHG Protocol, as follows:

- Scope 1 includes the direct emissions
- Scope 2 includes indirect electricity emissions
- Scope 3 includes indirect natural gas supply chain emissions

3. Results

Figure 3 portrays the carbon intensity of hydrogen produced by the assessed process in comparison to other hydrogen production methods (in kilograms of CO2 equivalent per kilogram of hydrogen produced).

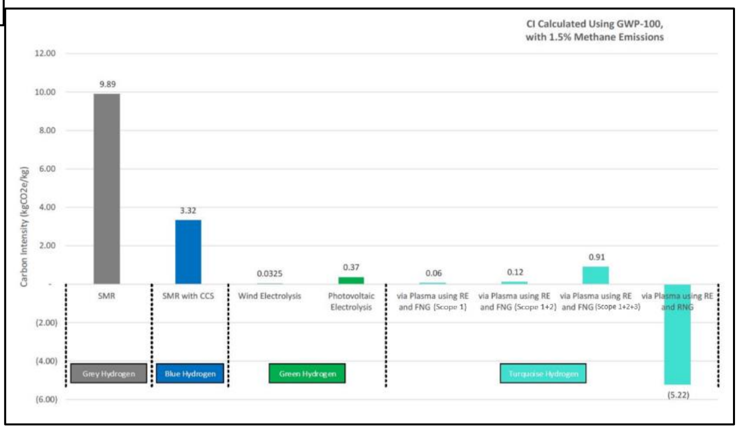

Fig. 3. Comparison of hydrogen production methods' carbon intensity

It is shown that hydrogen produced by this process has an aggregated carbon intensity (scopes 1+2+3) of 0.91 $kgCO_{2eq}/kg$, that is around 91% less than that of conventional grey hydrogen produced by steam methane reforming.

Additionally, what is interesting to note, is that the main emissions of methane pyrolysis via thermal plasma come from the natural gas supply chain (scope 3), as they constitute around 87% of total emissions for a base case of 1.5% leak rate.

Furthermore, replacing the fossil natural gas used by renewable natural gas made by anaerobic digestion of food waste leads to a negative carbon intensity of -5.22 $kgCO_{2eq}$ /kg that is significantly less than green hydrogen produced via electrolysis and renewable energy.

Regarding renewable natural gas, two other renewable natural gases are assessed using the same hypotheses, and are presented in Figure 4. The comparison is made on the percentage of the renewable natural gas required to be mixed with the fossil natural gas as process input to reach carbon neutrality (i.e. 0 $kgCO_{2eq}$ /kg hydrogen).

The advantage of blending with renewable natural gas is the negative carbon intensity of the feedstock as renewable natural gas is made from organic materials that have absorbed CO_2 during their lifetime and were transformed to renewable natural gas that is pyrolyzed in the process instead of breaking down naturally and releasing the absorbed CO_2 back.

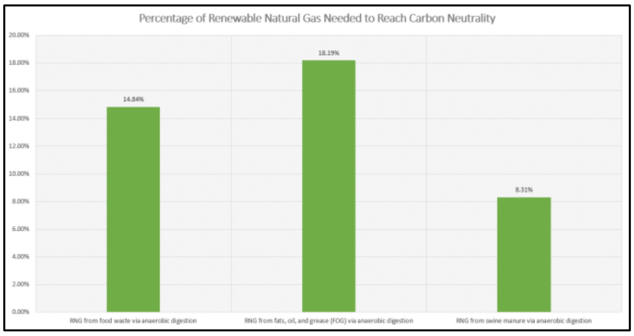

Fig. 4. Comparison of Different Renewable Gases as Process Input

It is shown that the chosen renewable natural gas for the base case (made from food waste via anaerobic digestion) leads to carbon neutrality at a percentage that falls in between renewable natural gas made from fats, oil, and grease, and renewable natural gas made from swine manure.

4. Conclusion

The main conclusions of the LCA study can be summarized as follows:

1- Pyrolysis of methane via thermal plasma leads to products with a low carbon-intensity
2- The total emissions of the process are primarily due to emissions associated with the purchased electricity and the supply of natural gas
3- When using low-carbon electricity (notably wind power), 87% of the emissions come from the supply of natural gas, and the total carbon intensity of hydrogen reaches 0.91 $kgCO_{2eq}$/kg for a leak rate by 1.5%
4- The pyrolysis of methane by thermal plasma not only emits less greenhouse gases than the electrolysis of water, but is also significantly less energy intensive
5- The use of renewable natural gas leads to a negative carbon intensity for hydrogen at low percentages of renewable natural gas (10-20%)

Compared to other hydrogen production methods, hydrogen produced by methane pyrolysis via thermal plasma and renewable natural gas is by a significant margin the least greenhouse gas emitting method.

5. References

[1] L. Fulcheri, V. Rohani, E. Wyse, N. Hardman, & E. Dames. An energy-efficient plasma methane pyrolysis process for high yields of carbon black and hydrogen. International Journal of Hydrogen Energy, 48(8), 2920-2928. (2023).
[2] IEA. Global Hydrogen Review 2022. IEA, Paris. (2022)
[3] S. Timmerberg, M. Kaltschmitt, & M. Finkbeiner. Hydrogen and hydrogen-derived fuels through methane decomposition of natural gas–GHG emissions and costs. Energy Conversion and Management: X, 7, 100043. (2020).
[4] J. Diab, L. Fulcheri, V. Hessel, V. Rohani, & M. Frenklach. Why turquoise hydrogen will Be a game changer for the energy transition. International Journal of Hydrogen Energy, 47(61), 25831-25848. (2022).